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Position paper

Domain-general problem solving skills and education in the 21st century

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1. Executive summary

This position paper is aimed at highlighting the relevance of domain-general problem solving skills for a comprehensive approach to contemporary education. We argue that education in the 21st century needs to be comprehensive in the sense that it should equip students with *domain-general* problem solving skills in addition to *domain-specific* factual knowledge and problem solving strategies.

In this position paper, we argue that contemporary educational systems fall short of addressing the societal and individual needs to teach and to foster domain-general problem solving and that education needs to be extended. To this end, researchers face three main challenges: (1) to increase the relevant stakeholders' awareness of the existence and the importance of domain-general problem solving skills, (2) to optimize the ways in which such skills can be assessed, and (3) to explore ways to foster students in developing and maintaining these skills.

1.1. Accelerating changes in today's world and why a new focus is needed

The transition from the 20th to the 21st century has been accompanied by dramatic changes in virtually all areas of society. The globalization and growth of technology have led to fundamental and lasting changes in the societies of the 21st century, also labeled technological societies. Crucially, these changes are reflected in the types of problems encountered in everyday life and, thus, in demands for the skills students need in order to successfully master life's challenges. Whereas factual knowledge is almost instantly accessible nowadays, we are increasingly faced with dynamically changing, intransparent, and complex problem environments across a wealth of situations and contexts. It is the mission of education to adequately supply students not only with factual knowledge and domain-specific problem solving strategies (which are crucial in and of themselves as well) but also with a broader set of skills required in today's societies. We argue that, in their current state, many educational systems most likely fall short of fully exploiting the cognitive potential of their student population in the area of domain-general problem solving, which is particularly relevant for successful educational, professional, and personal development in the 21st century.

1.2. Domain-general problem solving skills in everyday contexts

Without doubt, domain-specific problem solving skills and specific factual knowledge have high explanatory power with regard to tackling a routine task or a problem in a specific field, but they are limited to narrow domains. Because of this,

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several cross-curricular skills have been in the spotlight and have been considered highly relevant for citizenship in contemporary societies in addition to domain-specific skills. Domain-general problem solving is arguably the most prominent of the cross-curricular skills that have a particular relevance for education. That is, domain-general problem solving encompasses the very skills set that are necessary for a person to adapt to the cross-curricular problem environments typical of contemporary societies. It touches on several cognitive and noncognitive skills such as information processing, representation and evaluation of knowledge, reasoning, self-regulation, metastrategic thinking, proactive planning, and decision-making. The 2012 cycle of the Programme for International Student Assessment (PISA), which is run on a triennial basis by the Organisation for Economic Co-operation and Development (OECD), recently adopted a framework for domain-general problem solving. This framework provides a theoretical conceptualization that might serve as an interesting starting point for how to integrate domain-general problem solving and its components into contemporary education and national school curricula. To this end, we argue that most educational systems are relatively efficient in transmitting knowledge that is organized according to the principles of specific disciplines. This is a significant strength of the current systems, but as teaching is organized within disciplinary boundaries, more general conceptual frameworks and intellectual skills do not receive enough attention. This should lead to some rethinking of how permeable these boundaries should be and the extent to which they allow for adequate teaching of the entire set of skills necessary for the next generation of citizens.

1.3. Domain-general problem solving and its current role in educational assessment

Several educational large-scale assessments have been launched worldwide over the last two decades. These large-scale assessments, among them the PISA survey, are an attempt to quantify the performance of educational systems and to monitor their development over time. Thus far, PISA and other large-scale assessments have tried to adapt to the emerging demands implied by societal changes to a greater extent than national school curricula. This is exemplified by a strategy adopted by the OECD to cover more general and transversal skills in the international PISA assessment cycles in order to complement domain-specific skills. Importantly, domain-general problem solving was assessed in the PISA 2012 cycle with international comparisons across more than 40 countries. The results of these international comparisons indicate that domain-general problem solving skills might have been neglected in contemporary education. We argue that these and results from other large-scale assessments have relevant implications for educational systems. We further argue that we need to put forth more focused efforts to understand and directly address some of the problem areas that have been revealed by such assessments.

1.4. How can we facilitate the learning of domain-general problem solving skills?

In the technology-rich and fast-paced societies of the 21st century, we encounter problem situations on a daily basis. These problem situations need persistent, self-regulated, cognitively complex, and planned actions in order to be solved. Besides domain-specific problem solving skills, students need to be equipped with a set of diverse skills and exploration strategies that can be transferred to a number of situations and that are applicable across several domains. We argue that this development is in line with the inherent assumption of any educational effort that skills can be transferred to other contexts and contents. We acknowledge that empirical evidence on the transfer of cognitive training and interventions is mixed or modest in magnitude but also indicates the value of facilitating general thinking skills. To this end, we argue that the teaching of domain-general problem solving skills needs to be more explicitly embedded in domain-specific curricula by incorporating such skills into national school curricula and national standards. This process can be facilitated by the use of intelligent and integrated learning and assessment tools and specific interventions designed to strengthen the domain-general components of domain-specific teaching.

1.5. Where are we headed? Engaging educators in the teaching of domain-general problem solving skills

We argue that it is the link between everyday teaching practices and scientific discourse that needs to be strengthened in order to initiate a lasting structural shift. We will explore how a comprehensive and joint approach might advance knowledge on how to develop domain-general problem solving and on how to ensure the necessary shift toward comprehensive education for the next generation of students.

2. Accelerating changes in today's world and why a new focus is needed

The world of today is changing rapidly, perhaps more rapidly than ever. In the labor market, for instance, assembly line jobs in the automotive industry or in manufacturing were common five decades ago. Today, the number of people working on assembly lines has diminished dramatically, and machines and computers carry out tasks previously performed by human workers. Whereas some jobs have almost entirely disappeared from the surface of the labor market, new jobs with new demands have emerged, and the task composition of many other jobs has changed radically. In an empirical investigation of these changes, Autor, Levy, and Murnane (2003) reported that in the 1960s, routine cognitive and manual activities that are characterized by the repeated practice of similar tasks and that are located within highly specified domains began leaving workplaces in the U.S., be it in industry, service, or other occupations (Autor et al., 2003). At the same time, new demands began to arise as tasks in virtually any job extended across their traditional domain-specific boundaries, and the frequency and importance of tasks that were of a more general and transversal nature began to increase considerably across occupations.

As daily work life has been shifting away from routine tasks mostly located within a specific domain toward nonroutine tasks that require skills in a number of domains and even across them, the skills needed to master these tasks are changing as well. Whereas domain-specific knowledge and strategies are often sufficient for solving routine tasks, domain-general problem solving skills are considered to play an important role when humans have to master new situations involving nonroutine tasks in today's world. These skills are highly relevant for successfully mastering new societal challenges, and the acquisition of such skills should be a core mission of education in the 21st century (Autor et al., 2003; Greiff et al., 2013; Griffin, McGaw, & Care, 2012; OECD, 2012a). The problem solving skills that individuals need to acquire are domain-general in the sense that the relevant cognitive and noncognitive processes are of a transversal nature and extend across several domains. They are relevant for a variety of different nonroutine tasks in education, the workplace, or somewhere else (Autor et al., 2003; Kalyuga, Renkl, & Paas, 2010; OECD, 2013a). In recent outlooks, domain-general problem solving skills have been highlighted as crucial factors for assuring prosperity at individual and societal levels (Griffin et al., 2012; OECD, 2012a, 2014).

Teachers, school principals, and policy stakeholders are now faced with the specific implications of this shift. They need to ask, as expressed by the words already put forth by Drucker (1954) 50 years ago, how to provide society with the tremendous numbers of highly skilled and highly trained individuals needed in today's work force. Educational systems that fail to acknowledge and act upon these demands are at risk of falling behind. We argue that a number of recent scientific developments, coming primarily from the fields of cognitive and developmental psychology, the learning sciences, and educational large-scale assessments, can add to the understanding, integration, and facilitation of domain-general problem solving skills and, thus, to helping education move into the 21st century.

3. Domain-general problem solving skills in everyday contexts

There is little doubt that students leaving school as good problem solvers will have an advantage in life over students with lower levels of problem solving skills (Davidson & Sternberg, 2003). Therefore, the OECD decided to implement an assessment of domain-general problem solving[1] in the 2012 cycle of the PISA survey, one of the most renowned educational large-scale assessments worldwide. PISA assesses 15-year-old students (roughly at the end of compulsory schooling) in over 34 OECD member countries and 31 associated countries across the globe. Its major assessment domains have focused on classical curricular areas such as reading, math, and science (OECD, 2009, 2013a). However, there is a fourth domain in each assessment cycle in which PISA assesses knowledge and skills that are vital in modern societies but cannot be allocated to the traditional assessment domains. It is thereby acknowledged that it is important not only how well educational systems succeed at promoting domain-specific skills in the different subjects but also the extent to which schooling produces the (problem solving) capacities that are needed in the application of knowledge in everyday life across domains (Bransford, Brown, & Cocking, 2000).

Grounded in cognitive science and in the field of educational psychology (e.g., Funke, 2010; Greiff et al., 2013; Mayer & Wittrock, 2006; Novick & Bassok, 2005), domain-general problem solving skills in PISA 2012 are defined as "an individual's capacity to engage in cognitive processing to understand and resolve problem situations where a method of solution is not immediately obvious. It includes the willingness to engage with such situations in order to achieve one's potential as a constructive and reflective citizen" (OECD, 2014, p. 30). This capacity rests upon complex cognitive processes such as planning a sequence of actions, decision-making, and knowledge acquisition, all of which have to be coordinated to address a specific problem situation (Funke, 2010; Raven, 2000). It further includes aspects of self-regulation (Wirth & Leutner, 2008) and the use of heuristics (Gigerenzer, 2008). In fact, decision making in complex problem solving situations often requires the intelligent use of heuristics. Knowing when the use of a heuristic (e.g., tallying or recognition) is appropriate and when a deep analysis of the problem situation is warranted (prescriptive question; Gigerenzer & Gaissmaier, 2011) is an important feature of proficient problem solving. In this, domain-general problem solving involves different processes that are defined as separate facets in PISA 2012 (Mayer & Wittrock, 2006; Novick & Bassok, 2005; OECD, 2014): Students have to establish an understanding of the problem situation (exploring and understanding), identify the specific set of subproblems to be solved and formulate hypotheses about relevant aspects (representing and formulating), plan and carry out a solution (planning and executing), and monitor and evaluate their progress (monitoring and reflecting).

This conceptualization is vividly illustrated by one of the PISA 2012 tasks ("Lamp"; OECD, 2014). In this task, students have to determine whether a lamp is not working because (a) the switch is malfunctioning, (b) there is no power, or (c) the light bulb needs to be changed (OECD, 2014, p. 30). The students are asked to explore this computer-based task, to formulate hypotheses, to provide a solution, and to monitor their progress. Although it is fully acknowledged that domain-specific knowledge about electric circuits influences performance on this task (e.g., Dunbar & Fugelsang, 2005), domain-general strategies that are helpful across domains and problem situations such as systematically varying all aspects of the problem to determine the cause of the problem (e.g., exchanging the light bulb while holding all other variables constant) play important roles as well (Vollmeyer, Burns, & Holyoak, 1996). Such systematic strategies are, of course, also

[1] In PISA 2012, domain-general problem solving was labeled *Creative Problem Solving* (OECD, 2014).

useful in classical curricular problem situations, but it should become clear to students that the use of such strategies is not bound to a specific curricular domain (Wüstenberg, Stadler, Hautamäki, & Greiff, 2014). The relevance of the intelligent use of strategies across domains was acknowledged by the OECD (2014) as follows: "[the students] who solve problems efficiently, even when they [the problems] arise outside of their [the students'] field of expertise, have mastered general reasoning skills, can apply those skills where appropriate, and are motivated to engage with unfamiliar problems" (OECD, 2014, p. 29).

This quote further suggests that, in addition to the proficient use of strategies, domain-general problem solving is related to other cognitive abilities such as fluid intelligence. In fact, the nature and strength of this relation has been a controversial topic of discussion for years with positions ranging from (almost) complete independence (e.g., Joslyn & Hunt, 1998) to identity (e.g., Wittmann & Sü., 1999). Recent research has adopted a more balanced position: Reasoning, working memory, and simple problem solving abilities that are found in virtually any definition of fluid intelligence (Sternberg & Berg, 1986) are considered precursors and important attributes of more complex domain-general problem solving skills, but they are not sufficient for ensuring that a person will be a good problem solver across domains. That is, a set of additional skills is needed for domain-general problem solving (Funke, 2010; Raven, 2000; Wüstenberg, Greiff, & Funke, 2012). The conceptual understanding that domain-general problem solving is related to, but at the same time, provides added value to fluid intelligence has been corroborated by recent studies that have shown that domain-general problem solving was able to explain supervisor ratings of overall job performance in academic achievement (e.g., Wüstenberg et al., 2012) and in a variety of occupations (e.g., Danner, Hagemann, Schankin, Hager, & Funke, 2011).

The predictive value of domain-general problem solving in educational and occupational contexts is a reflection of the relevance of these skills in daily work life in the 21st century. As an illustrative example, consider the role of a secretary who works in a contemporary business company. The secretary's tasks are likely to require skills in a number of domains that were not mentioned in the job description of a secretary only a few decades ago (cf. the job description of a secretary in 1976; U.S. Department of Labor, 1976). That is, tasks that were formerly reserved for managers such as planning and organizing events and meetings have now become part of the secretary's job. For instance, to organize and schedule a business meeting, the secretary obviously relies on domain-specific solutions, such as standard procedures for the planning and scheduling of meetings and events. To do this, a combination of factual knowledge and domain-specific problem solving strategies will usually suffice. However, in some cases, new situations might arise or situations might unexpectedly change in such a way that existing domain-specific knowledge and strategies will not suffice to solve the problem. This is when domain-general problem solving comes into play. If some of the meeting's attendees need to reschedule due to a last-minute delay, several actions with multiple constraints need to be initiated such as finding alternative solutions or communicating the new situation. This might include the need to find a new meeting venue, to quickly inform people of the delay, to adequately communicate the new situation, to explore alternative solutions, and to make swift and correct decisions and adjustments. On a more general level, this will require that the secretary consider the dynamics inherent to the new situation, its multiple and interconnected variables, information that may be incomplete, a situation that may be nontransparent and opaque, elements that may change dynamically, as well as multiple and only partially known constraints (Funke 2010; Greiff et al., 2013; Osman, 2010). If all this happens under a great deal of time pressure, the secretary will not be able to execute a full and systematic analysis of this complex situation but will rely in part on heuristics and their appropriate use to make quick and appropriate decisions (Gigerenzer, 2008).

Taken together, both the example of the secretary and of the PISA 2012 "Lamp" task point toward the importance of both domain-specific and domain-general skills in solving problems of virtually any kind. However, the relevance of domain-general skills is not undisputed as a vast number of studies conducted at the end of the last century emphasized the importance of domain-specific problem solving skills in comparison with domain-general skills (Larkin, 1989). As a consequence, domain-specific problem solving strategies are often referred to as "strong methods", whereas domain-general strategies are labeled "weak methods" (Jonassen, 2000, p. 68). This view has been integrated into contemporary theories on problem solving and, indeed, domain-specific skills are highly relevant as specific problems are always domain-bound. However, the prominent role of domain-specific knowledge for problem solving outcomes does not imply that domain-general skills are insignificant. Also domain-general skills are part of concurrent problem solving theories, and the distinction between domain-specific and domain-general skills is frequently used as an important characteristic in the problem solving literature (e.g., De Jong & Ferguson-Hessler, 1996; Robertson, 2001). According to Kalyuga et al. (2010), domain-general problem solving skills may have less explanatory power than domain-specific strategies for solving a specific problem but are important and helpful in problem situations across domains (i.e., the bandwidth-fidelity dilemma; Kalyuga et al., 2010). Domain-general skills may also contribute to successful solutions when people encounter new problem situations requiring nonroutine actions in which they cannot rely on known domain-specific strategies (Kalyuga et al., 2010; Ones & Viswesvaran, 1996). Nevertheless, we do not claim that domain-general skills are in any way more important for solving specific problems than domain-specific skills because (a) research on experts versus novices suggests that skilled problem solvers in a domain use little general knowledge compared with domain-specific knowledge, (b) various (stand-alone) domain-general problem solving courses and books have had little empirically demonstrable effectiveness, and (c) domain-general knowledge cannot be easily transferred to other problem situations (cf. Larkin, 1989; Robertson, 2001). It is important to note that domain-specific and domain-general problem solving are not two distinct categories but are considered to be two ends of a continuum. For instance, Larkin (1989) defined a level of generality between domain-general and completely domain-specific problems and claimed that strategies that are somewhat domain-general may transfer to several (but not all) domains.

In summary, we argue that domain-general problem solving skills are, both conceptually and empirically, relevant for ensuring a comprehensive approach to education. In the last two decades, however, educational research has been strongly (and almost exclusively) focused on domain-specific skills. We argue that researchers, educators, and policy makers have lost sight of the fact that domain-general problem solving skills are relevant as well. We share the view of Sternberg (1995) who, at the end of the 20th century, had already issued the warning that research on the general mental processes involved in problem solving had been wantonly neglected and that we needed to understand more about how domain-general problem solving fit into educational systems. To this end, international large-scale assessments have recently tested domain-general problem solving and other so-called "21st century skills" (Griffin et al., 2012). They have produced interesting results with regard to the assessment, the understanding, and ultimately the facilitation of these skills beyond domain-specific disciplines.

4. Domain-general problem solving and its current role in educational assessment

Even before the launch of international large-scale assessments, the intention to measure educational outcomes beyond factual knowledge had been an important topic. Assessments of general cognitive ability such as tests of fluid intelligence would have been the most obvious candidate, as these tests have been used in a number of contexts, but due to the easy misinterpretation of the concept of intelligence and because of its low amenability, such assessments in schools raised several concerns (Adey, Csapó, Demetriou, Hautamäki, & Shayer, 2007). However, researchers in many countries have been exploring the assessment of broad thinking skills and general cognitive abilities. These assessments included, among others, critical thinking (King & Kitchener, 1994), inductive reasoning (Csapó, 1997), learning to learn (Hautamäki et al., 2002), and domain-general problem solving (Greiff et al., 2013; Klieme, 2004). Domain-general problem solving skills in particular have received growing attention and have appeared in several national and international educational assessments; for instance, in Finnish municipalities, in Hungarian schools, or in the Luxembourgish educational system. Among international efforts, PISA has been a pioneer (OECD, 2014), but similar efforts to incorporate domain-general problem solving have been undertaken in other large-scale assessments such as in the ALL (Adult Literacy and Life Skills Survey; Statistics Canada & OECD, 2005) and, more recently, in the PIAAC study (Programme for the International Assessment for Adult Competencies; OECD, 2013b).

These examples of recurrent efforts within national and international large-scale assessments are indicative of a more general move toward the comprehensive coverage of domain-general skills. For instance, in the ATC21S initiative (Assessment and Teaching of 21st Century Skills; Griffin et al., 2012) as well as in PISA 2015, domain-general problem solving skills will be assessed on a collaborative level. Thus, the focus will shift from individual skills to social components that may play a role in a number of situations. In PISA 2015, chat-based simulations will be employed to test students' skills in solving problems collaboratively, including social and communicative aspects that establish a shared understanding of the problem at hand or provide essential feedback to team members while maintaining the cohesion of the members to achieve group goals (OECD, 2012b).

The evidence produced by these efforts is likely to lead to a broad and vivid discussion in the public. A prime example of this is the current discussion that centers on the PISA 2012 problem solving assessment report that was published in a separate volume by the OECD in 2014. The PISA report was among the first to compare students' levels of domain-general problem solving across countries and across educational systems (OECD, 2014). Interestingly, the overlap between domain-general problem solving and the three content domains traditionally assessed in PISA (mathematics, science, and reading) was considerably lower than the overlap between the three classical domains even though the contextual embedding for all tasks was specifically targeted at contexts typically encountered by 15-year-old students (61% shared variance vs. 77% shared variance, respectively). This indicates that domain-general problem solving as assessed in PISA 2012 might to some degree tap into distinct cognitive processes that are not covered by domain-specific skills and that are relevant educational outcomes. Indeed, the PISA problem solving report yielded several important findings with direct and strong implications for educational systems across the globe. For instance, over 20% of the students tested in PISA performed at a proficiency level of 1 or below in domain-general problem solving (with Level 6 denoting the highest proficiency level of mature and independent problem solving). These students tend to explore new problem situations only if they have encountered almost identical problem situations before. However, they are unable to comprehensively explore new problem situations. In general, the exploratory behavior of students at or below Level 1 is characterized by unsystematic patterns of behaviors and interventions. That is, these students are unable to plan ahead or to set subgoals when faced with a new and complex problem environment. On average for the OECD, one out of five students shows this troubling level of performance, but the percentage of students at this level varies across countries and can reach up to 50% or 60% in some countries. We argue that substantial parts of the entire student population in several countries are in danger of progressively falling behind, which in turn will lower their chances of succeeding in life (Kuncel, Hezlett, & Ones, 2004; Robbins et al., 2004).

These and other results that can be found in the PISA 2012 report give rise to a number of highly relevant questions for anybody involved in or concerned about education. For instance, to what extent do the countries performing at the lower end of the scale with a high percentage of students clustering at low proficiency levels (e.g., Hungary, Spain, Israel) have different teaching practices than better performing countries? Is there a causal link between these teaching practices and these lower performance levels? Questions such as these will naturally place the relevance of domain-general problem solving skills and of other transversal skills at the top of the agenda of many policy makers and educators, but they are also of interest to the wider public. We hope this discussion will not stop at the doorstep of schools but will find its way into the classroom through direct and actionable measures that have a palpable and sustainable impact on curricular priorities.

5. How can we facilitate the learning of domain-general problem solving skills?

Initiatives aimed at fostering general cognitive abilities in the classroom have been a declared goal of education since the beginning of formal schooling, but because of the lack of a valid underlying conceptual framework and proper instructional methods, such a goal could not be translated into palpable educational activities even though a plethora of trainings were developed to foster thinking and problem solving skills (Costa, 1991; Hamers & Overtoom, 1997). Generally speaking, these developmental programs took one of two different approaches. The first approach was dominated by domain-general problem solving courses that were direct stand-alone programs with separate lessons outside of the traditional school subjects. However, there is no firm empirical evidence that such courses had significant or lasting effects (Jonassen, 2000; Larkin, 1989). The second approach included research on infusion, enrichment, transfer, and embedding, and it used modified teaching materials for the training of broad thinking skills such as domain-general problem solving. The rationale behind this is that similar cognitive processes are required for a number of tasks in varying contexts. Therefore, these processes can be detached from the actual content and are, thus, transferable to new contents and contexts. The content-based methods (Csapó, 1999), the "thinking curriculum" (Resnick, 1987), and the "thinking science" (Adey, Shayer, & Yates, 1989) are early examples of such interventions that have strong theoretical foundations and were tested in controlled empirical experiments. Several of them were shown to have a broad and lasting impact on educational outcomes and have been integrated into mainstream educational processes through dedicated programs such as the Cognitive Acceleration through Science Education (CASE; Adey & Shayer, 1993) or Klauer's training of inductive reasoning (Klauer, 2014). In addition to these interventions, which are aimed at supporting the individual student, considerable research efforts have addressed the transfer of learning skills in collaborative settings (e.g., teamwork, team learning, communication skills; cf. the assessment of collaborative problem solving in PISA 2015; OECD, 2012b). Dochy, Gijbels, Raes, and Kyndt (2014) provide a compelling overview of the origin and history of team learning approaches in education, thereby focusing on problem-based learning, its antecedents, and its outcomes.

It is along the lines of such theoretically founded and empirically guided programs of student learning that we see the potential for education to invest in students' domain-general problem solving skills and to tackle the issue of the trainability of broad thinking skills that are relevant across a number of domains. Importantly, a core assumption in the PISA study is that the set of skills associated with domain-general problem solving and the development of such skills can be fostered in school because the strategies relevant for domain-general problem solving are malleable (OECD, 2014). Interestingly, problem solving interventions can also help students to develop a set of structured, semi-structured, and heuristic approaches when tackling new problem situations, thus suggesting that it is possible to equip students with a portfolio of relevant problem solving strategies including, for instance, deep analysis and heuristics that are relevant in new problem situations (Barak, 2013). Lorch et al. (2010) give an example of how such interventions might make their way into the classroom by showing that both self-conducted experiments and explicit instruction facilitate students' strategic approaches in a complex environment. The effect reported by Lorch et al. (2010) was observed across several domains and was found even months after the experiment was conducted.

This line of thinking leads directly to the question of which specific actions might be needed to enhance students' problem solving skills and how these efforts can be incorporated into everyday teaching with the ultimate goal of providing students with sufficient learning opportunities. The task of researchers is to develop a sound research agenda that will inform educators and policy makers how to reach this goal. As an initial starting point, we consider three major challenges: (1) raising awareness of the existence and relevance of domain-general problem solving skills, (2) developing and optimizing assessment tools to allow for integrated assessments and learning experiences, and (3) establishing interventions and the training of domain-general problem solving.

5.1. Challenge 1: Raising awareness of the existence and relevance of domain-general problem solving skills

Given that all education proceeds either implicitly or explicitly on the assumption of transfer (Banich & Caccamise, 2010; Perkins & Salomon, 1989), one challenge currently faced is how to raise awareness of the existence and relevance of domain-general problem solving and how to find ways to explicitly integrate problem solving skills into the extant domain-specific national school curricula. Importantly, in recent years, national curricula have been established in a number of countries to set standards that indicate which domain-specific skills students should learn at specific ages. For instance, students are taught according to Next Generation standards in the U.S. (Stage, Asturias, Cheuk, Daro, & Hampton, 2013), and every teacher in German schools is familiar with the German "Bildungsstandards" (Kauertz, Fischer, Mayer, Sumfleth, & Walpuski, 2010). A closer look at these standards reveals that they often contain keywords reflecting skills such as "problem solving," but these keywords are seldom filled with content. Keeping this in mind, we argue that direct and actionable measures are needed to adequately integrate and represent domain-general problem solving in national school curricula.

First, we argue that domain-specific problem solving skills that are taught in school are accompanied and can be complemented by more domain-general problem solving skills that are relevant across domains. Put differently, complex problem environments in subjects as different as history and chemistry share some underlying principles. As an example, many highly interrelated variables are involved in both historical events (e.g., participating actors and influencing factors at the beginning of WWI) and chemistry (e.g., elements and their reactions when molecules form), both requiring the skill to generate a correct mental representation of the interconnected and complex problem environment (Holyoak, 1985; Novick & Bassok, 2005). Consequently, when a general principle is taught in multiple contexts and includes examples that demonstrate wide application of what is being taught, students are more likely to abstract the relevant features of concepts and to develop a flexible representation of knowledge that is applicable across domains (Bransford et al., 2000; Gick & Holyoak, 1983). We are not suggesting that "problem solving" be introduced as an explicit subject at school, but we are suggesting that teachers, irrespective of their specific subject, should emphasize and train students to apply relevant problem solving processes beyond the specific context and encourage students to discover similarities and recurring principles across problem situations. Such a practice needs to be explicitly integrated into national school curricula.

Second, we advocate the inclusion of domain-general problem solving in international and national large-scale assessments as a recurring domain. Results coming out of these assessments will provide interesting tools by which to monitor the development of proficiency levels in problem solving and, thus, to raise the wider public's awareness of the relevance of domain-general problem solving. For instance, comparing schools, districts, or countries that include the teaching of domain-general problem solving in their curricula with those that do not will yield important information about the effectiveness of teaching and of national curricula. Longitudinal studies will allow countries to evaluate the link between domain-specific and domain-general skills and their connection to later success in life. Such studies will also address additional questions such as whether the integration of domain-general problem solving comes at the expense of domain-specific skills.

5.2. Challenge 2: Developing and optimizing assessment tools to allow for integrated assessments and learning experiences

A major problem in contemporary education faced by teachers of classes with 20 or more students is that the strategies these students apply when solving domain-general problems remain largely invisible. Obviously, this makes it difficult to teach and facilitate these skills and strategies. To this end, recent developments in the field of educational technology now allow for the development of environments that, on the one hand, require the use of domain-general problem solving strategies and that, on the other hand, have the advantage of making these strategies visible to educators, who are ultimately responsible for fostering these skills (Graesser, 2013; Ifenthaler, Eseryel, & Ge, 2012). On a specific level, we argue that students' behavioral data recorded during the problem solving process can readily be used in integrated assessment and learning environments to make individual strategies directly visible to teachers in the classroom. As an example, consider the "Lamp" item used in PISA (OECD, 2014) in which students have to determine why a lamp is not working. Automatic log file analyses can reveal whether students employ an efficient or inefficient exploration strategy (e.g., varying more than one variable at a time; Chen & Klahr, 1999) and how flexibly they are able to adapt their strategy to the requirements of the problem situation (Funke, 2010). Detailed log file analyses provide teachers with feedback about the overall proficiency levels of their students and can support teachers in identifying on a very fine-grained level the areas in which their students' learning is weak. This is a prerequisite for providing tailored support to students to help them overcome their individual weaknesses and is at the core of what is meant by differentiated learning or differentiation in education (Tomlinson, 1999). Even further, automatic log file analyses of problem solving behavior can be used to provide immediate performance feedback to students (Ritter, Anderson, Koedinger, & Corbett, 2007; Williamson, Mislevy, & Bejar, 2006). For instance, if a student repeatedly tackles a given problem inefficiently and explores the dynamically changing problem situation in a suboptimal way, these issues can be automatically detected, and the learning tool can provide feedback to the student by suggesting a different strategy. This strategy, in turn, can be transferred to other problem situations as well (Chen & Klahr, 1999). Thus, automated training of domain-general problem solving skills (i.e., scaffolding; Gobert, Sao Pedro, Razluddin, & Baker, 2013) can be used to complement teachers' efforts to enhance students' deep comprehension through an in-depth automatized analysis of students' behavior (Ifenthaler et al., 2012; Williamson et al., 2006). This might, in fact, be an easy way to support teachers in their efforts to optimize their students' skills in an educational world with scarce resources.

5.3. Challenge 3: Establishing interventions and the training of domain-general problem solving

Once we have succeeded in making domain-general problem solving strategies visible to educators, the field will be in a much better position to integrate targeted interventions into teachers' everyday reality. This would counter the criticism of many educators that large-scale assessments are rather disconnected from the actual reality of teaching (Birenbaum et al., 2006). In this spirit, we will outline a set of principles that education would have to adopt to meet the goals of directly and systematically increasing domain-general problem solving and facilitating the acquisition of knowledge across domains. Facilitating domain-general problem solving skills is no easy task due to the fact that diverse cognitive processes are involved in domain-general problem solving. Such processes include focusing on relevant information (and disregarding irrelevant information), mentally representing acquired knowledge and associating it with extant knowledge, choosing specific actions and operators when trying to reach a specific goal, and checking and evaluating mental models and their validity in reference to evidence (cf. the PISA processes mentioned above). In any developmental phase, education must lead students to develop and refine these cognitive skills and, in doing so, develop their proficiency in successfully solving domain-general problems. These educational goals must be in line with the developmental possibilities and constraints of successive phases. We propose the following steps as a framework that might govern this process and that derive from contemporary cognitive, psychometric, and developmental research (Bransford et al., 2000; Demetriou, Spanoudis, & Mouyi, 2011).

1. Educational interventions aimed at enhancing problem solving skills should capitalize on developmental milestones in order to make education relevant, appropriate, and useful for each phase of life. For example, preschool education must facilitate the knowledge and handling of the multiplicity of representations, points of view, and their relation to reality. In primary school, education must focus on the connections between concepts and operations and facilitate children to acquire awareness of their own inferential processes and how they might make use of these processes in different subjects. With the increasing skills of students to tackle complex cognitive processes, secondary and higher education should focus on developing strategic approaches and heuristics that can be applied to problem solving (such as the "if … then" stance) and their application across domains, build epistemological awareness about domains and their boundaries, and establish an awareness of underlying inferential processes and their usefulness across domains.
2. Problem solving may be improved by instruction that directly addresses the various aspects of more fundamental cognitive abilities such as working memory, attention, and executive control. That is, education should aim to improve students' skills to (a) monitor ongoing performance, (b) manage more than one task simultaneously, (c) organize items according to type and time of presentation, and (d) discard irrelevant information. All these skills, on the one hand, refer to fundamental cognitive operations, and on the other hand, are the building blocks of the complex cognitive operations required for successful problem solving. At the same time, the organization and presentation rate of material to be learned must take into account the current representational and processing abilities of students as described, for instance, by cognitive load theory. To this end, Van Merriënboer (1997) suggests that material should proceed from simple to complex with gradually diminishing levels of instructional support to facilitate the acquisition of knowledge.
3. Special attention should be paid to the de-contextualization of thinking processes and the inferences made from content and domain. For example, already in preschool, children may be trained to realize that the information in verbal statements is connected by inference. In primary school, directed comparisons across different types of arguments enable children to differentiate form from content and understand that principles of logic constrain inference. In adolescence, efforts in secondary educational settings all the way through higher education may focus on the formal aspects of different types of arguments and their underlying structure (Demetriou & Christou, in press).
4. In addition to these cognitive aspects of problem solving, students need to become aware of the organization and functioning of their own minds, and they must be able to adjust their actions and learning accordingly. In other words, they need to be equipped with meta-skills such as self-regulation. For example, mindfulness training could enhance self-monitoring skills, which, in turn, enhance executive control, thereby improving learning and problem solving capacities (Zelazo & Lyons, 2011). In secondary school and in institutions of higher education, adolescents may be guided to grasp the differences between formal disciplines (e.g., mathematics) and empirical disciplines (e.g., physics) and the underlying principles these disciplines might share or not share. This would enable them to evaluate the differences and the commonalities between the knowledge produced by these disciplines and how this might be relevant when facing new problem situations from a variety of domains (Demetriou et al., 2011).
5. Finally, domain-general problem solving is related to and involves all of the cognitive and noncognitive processes mentioned above. Thus, it should be demonstrated and practiced as such on a regular and frequent basis. Students should be educated in the foresight, anticipation, and formulation of alternative plans for various problems from a large number of different domains (Halpern, 1998). There are several instructional methods that demonstrate how this can be achieved, many of them well supported by empirical evidence. According to Chi (2009), for instance, interactive involvement and students' self-explanation when solving problems leads to deep understanding (e.g., asking and answering questions), whereas passive behavior (e.g., listening) creates only a shallow understanding of problems. Keeping Chi's (2009) framework in mind, we suggest that the teaching of domain-general problem solving should therefore include the active participation of students, followed by interactive group discussions about the difficulties they encountered during the process (Dochy et al., 2014). In such a process, the use of educational technology (see above) can be a great help to the teacher who serves as a moderator and guides learners' attention toward transferring the insights they developed from this situation to other problem situations. We suggest that the aforementioned framework and its five aspects be used as an initial starting point for a discussion centering on the question of how to cultivate students' domain-general problem solving skills within the given disciplinary boundaries of contemporary education.

6. Where are we headed? Engaging educators in the teaching of domain-general problem solving skills

On the one hand, cognitive and developmental research can provide specific suggestions for how to link cross-curricular skills such as domain-general problem solving with the everyday reality of teaching. Along these lines and with regard to the specific suggestions made above, we argue that this integration is both necessary and possible. On the other hand, domain-general problem solving is hardly ever taught explicitly in school, and the PISA 2012 results are not the only indication that domain-general skills are not being routinely and sufficiently addressed. In fact, when it comes to domain-general problem solving, it is often assumed that students implicitly learn the set of necessary skills in school. Mayer and Wittrock (2006) were among the first to use the term *hidden curriculum* in the context of problem solving to describe the phenomenon that teachers usually provide little problem solving instruction and yet expect students to be able to solve new problems and to develop their domain-general problem solving skills.

However, such a passive approach will not suffice if we want to create educational systems and educational practices that are able to prepare students to meet the newly emerging demands of the 21st century. Indeed, there is a need for joint efforts between researchers, educators, and policy makers as well as targeted interventions organized by educators in schools. Such efforts must be aimed at assuring adequate preparation of the next generation of students for the challenges that await them and to equip them with domain-general skills that will allow them to tackle problems in domains in which they are non experts but that they will inevitably encounter in their lives. To this end, Herbert Simon and William Chase (Simon & Chase, 1973) highlight that it takes at least 10,000 h to gain deep knowledge in any area of expertise. Obviously, there is not enough time in a person's life to rely entirely on domain-specific problem solving and to become an expert in a large number of domains. This natural constraint might become even more intensified as the world becomes more diverse and splinters into self-regulated learning. Our hope is that domain-general problem solving will help to navigate successfully through diverse content areas in a rapidly changing environment. Research provides numerous starting points for an expansion of education that is (and should be) organized within disciplinary boundaries but is simultaneously obliged to comprehensively address the domain-general problem solving skills that students need in the 21st century. It is up to scientists to develop a sound and sustainable research agenda that, in turn, will inform educators and policy makers how to create sufficient learning opportunities for students. If these challenges are met in the long run and if educational systems manage to produce good problem solvers by providing sufficient learning opportunities, we will have successfully traveled along the path laid out by many scholars throughout the millennia who have voiced the opinion that an essential part of good education is giving students the opportunity to discover problem solutions by themselves. With the rapid changes and swiftly emerging new demands in today's world in mind, this challenge and the need for a strong implementation of domain-general learning opportunities may now be greater than ever before.

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